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Ubiquitous Nature of Event-Driven Approaches: A Retrospective View* (Position Paper)

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Abstract

This paper retrospectively analyzes the progress of event-based capability and their applicability in various domains. Although research on event-based approaches started in a humble manner with the intention of introducing triggers in database management systems for monitoring application state and to automate applications by reducing/eliminating user intervention, currently it has become a force to reckon with as it finds use in many diverse domains. This is primarily due to the fact that a large number of real-world applications are indeed event-driven and hence the paradigm is apposite.

In this paper, we briefly overview the development of the ECA (or event-condition-action) paradigm. We briefly discuss the evolution of the ECA paradigm (or active capability) in relational and Object-oriented systems. We then describe several diverse applications where the ECA paradigm has been used effectively. The applications range from customized monitoring of web pages to specification and enforcement of access control policies using RBAC (role-based access control). The multitude of applications clearly demonstrate the ubiquitous nature of event-based approaches to problems that were not envisioned as the ones where the active capability would be applicable. Finally, we indicate some future trends that can benefit from the ECA paradigm.

1. Introduction

In the mid and late eighties, the inability of database management systems (DBMSs) to monitor and trigger

alerts and notifications even for conventional applications such as inventory control (e.g., a part needs to be reordered when quantity on hand decreases below a certain number) prompted the work on automating the above to reduce or eliminate user intervention. At that time, process control applications had the capability to monitor system state and take appropriate actions. However, most of these systems were custom-developed and optimized for real-time operation and did not use a general framework for the purpose of monitoring and automation. A number of efforts at that time examined a large number of applications from diverse domains such as process control, power distribution, stock trading and portfolio management, network management, and the use of database in monitoring applications with the goal of developing a framework that could be used for all monitoring applications. Timeliness, near real-time response, well-defined semantics, and the ease of management of the system were the goals of this research and development.

The early explorers of the rule/trigger concept for monitoring were: HiPAC [1], Postgres [2], and ETM [3]. Although all of them had the same broader goal, their approaches and how they addressed the problem were very different. HiPAC, perhaps, took the most general approach of incorporating monitoring into a DBMS by assessing the impact on all components of a DBMS: knowledge model (or specification), query optimization, transaction management and recovery. The separation of an event from condition and action was promoted based on the role of their semantics as compared to other extant approaches of that time. The event component was separated for the first time and event operators (disjunction, sequence, and closure) were proposed. Coupling modes

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between event, condition, and actions were proposed and their effects were analyzed on transaction management. ECA paradigm was seen as a flexible mechanism for automating a number of diverse functionality in a DBMS, such as view materialization, constraint enforcement, situation monitoring, and access control. The Postgres work, on the other hand, concentrated on incorporating triggers into the Postgres framework. ETM (or event/trigger mechanism) explored the notion of active capability in the context of enforcing constraints in design databases using triggers and events. There was some activity among the DBMS vendors as well and the first commercial DBMS to incorporate triggers was surprisingly Interbase [4] which developed a DBMS from scratch in the late eighties.

The nineties saw a large amount of academic research activity in the application of active capability in the form of the ECA (event-condition-action) paradigm to object-oriented, object-relational, and Relational DBMSs. A large number of prototype systems were developed during that period. Since event component was the least understood part as compared to conditions and actions (conditions correspond to queries, and actions correspond to transactions), there were a number of event specification languages that were proposed along with their semantics and algorithms for their detection. Seamless integration of the ECA paradigm into Object-oriented and other systems were examined in detail to facilitate its incorporation into a number of systems. In addition, various implementation alternatives, such as integrated [5], agent-based [6, 7], and wrapper-based [8] systems for supporting the ECA paradigm were explored. Without differentiating between the event specification languages and the systems that included events and triggers, efforts in the literature to support active capability included (in alphabetical order):

ACOOD [9], ADAM [10], Alert [11], A-RDL [12], Ariel [13, 14], COMPOSE [15], Hipac [16], ODE [17, 18], REACH [19], Rock & Roll [20], RuleCore [21], SAMOS [22, 23], Snoop/Sentinel [24, 5], SEQ [25], STARBURST [26], UBILAB [27], and [28, 29]. A comprehensive introduction and description about most of these systems can be found in [30, 31] and an annotated bibliography on active databases up to 1994 can be found in [32].

In addition to the above, there were a number of other projects that used the concept of events – CORBA [33] being one of the earliest. The notion of events at a low level were being used in network management systems and TIBCO had an event-based system that was used for notification. In addition to the above, graphics user interfaces (GUIs) used event-based callbacks to carry out actions based on the movement of the cursor on the screen. Although the notion of events were used in many of the

above systems, their semantics, composition, and execution aspects were not precisely defined. Other systems that have some notion of events include Weblogic [34], ILOG Jrules [35], and Vitria BusinessWare Automator [36].

The impact of all of the above was that all of the commercial DBMS vendors incorporated the notion of triggers into their products. In addition, SQL3 [37] further refined the specification of triggers and now it is part of the SQL standard. Unfortunately, the trigger capability supported in DBMSs is not used as much as it could be on account of the lack of support from the vendors. A detailed study [38] indicated that banks and other targeted users who could really benefit from this feature were not using them because: i) there is not enough support from the vendors on the use of triggers, ii) methodology and guidance for the usage of triggers were not available, and iii) the performance aspect of the DBMS with the usage of large number of triggers has been largely ignored by the vendors. If the performance disadvantage continues, it is unlikely that the trigger mechanism will see a wide use in real-world applications.

Beyond the above, work continued on distributed event specification, semantics, and detection [39, 40, 41, 42, 43]. Sentinel [5] developed a complete global event detector (or GED) that had well-defined semantics and used it for a number of real-world applications, such as monitoring multiple DBMSs to check on the viability of war- and peace-time plans that could change dynamically based upon changes to independent databases such as weather, intelligence information, maintenance of vehicles required for operation of plans, etc. A number of tools for the ease of specification of events and rules as well as their analysis were developed by the Sentinel group (event/rule visualization [44], dynamic rule editors [45, 46], and rule analysis concepts and systems were developed [47, 48]).

At the same time, the power and utility of the ECA paradigm on non-database applications were being recognized. Even within the database realm, it was shown that the ECA paradigm can not only be used for monitoring the state of user-defined objects, but can also be used for monitoring the system state. This led to the support of multiple transaction models in a flexible manner [49, 50] using rule sets that could be changed at run time. These rule sets were defined on interesting system events such as acquire lock, release lock etc. Beyond this, the local event detector was decoupled from its DBMS bondage and re-implemented in Java so that it can be used with any stand-alone application written in Java [51]. Today, the notion of active capability does not connote anymore the usage in the context of databases but has been accepted and recognized as a functionality that can be used for any event-driven real-world applica-

tion. Not surprisingly, it is finding usage in many applications (e.g., work flow, access control, information interchange) as a large number of applications are indeed event-driven.

Today, there is consensus in the database and other communities on the ECA rules as being one of the most general formats for expressing rules in an event-driven application. The semantics of event specification has undergone some extensions from point-based (or detection) semantics to Interval-based semantics. More than that, the number of diverse applications for which it is being used in some form is the real testimony for ubiquitous nature of the abstraction and is the focus of this paper.

The rest of the paper is organized as follows. Section 2 briefly describes the definition of events, the need for interval-based semantics, and event detection. Section 3 provides a brief exposure to novel applications that have adapted the ECA paradigm in unforeseen ways. Section 4 contains where this concept is headed and Section 5 has conclusions.

2. Event Semantics, and Detection

An event is defined [52] to be an instantaneous, atomic (happens completely or not at all) occurrence of interest and the time of occurrence of the last event in an event expression (composition of events using event operators) was used as the time of occurrence for the entire event expression. An event, which is an indicator of happening was classified into primitive (e.g., depositing cash in a bank) or composite (e.g., depositing cash, followed by withdrawal of cash). Primitive events occur at a point in time (i.e., time of depositing). Composite events occur over an interval (i.e., the interval starts at the time cash is deposited and ends when cash is withdrawn). The primitive event that starts an event was termed *initiator* and the primitive event that completed the event was termed the *terminator*. Since the event expression (or a composite event) was detected as of the time of occurrence of the terminator, this was called detection or point-based semantics. For a primitive event, initiator is also the terminator. All event specifications assumed the above and detected composite events using different approaches. The operators of Snoop subsumed most of the event specification proposed in the literature.

Snoop identified, proposed, and developed the semantics and detection for a large number of event operators based on the applications analyzed in HiPAC and additional applications analyzed later. The most general semantics (termed *unrestricted* or *general*) detected a large number of composite events in the presence of multiple occurrences of the same event. This seemed unnecessary for a large class of applications. Hence the notion of parameter contexts (aka event consumption modes) were proposed in Snoop [53, 52, 54] to constrain the number

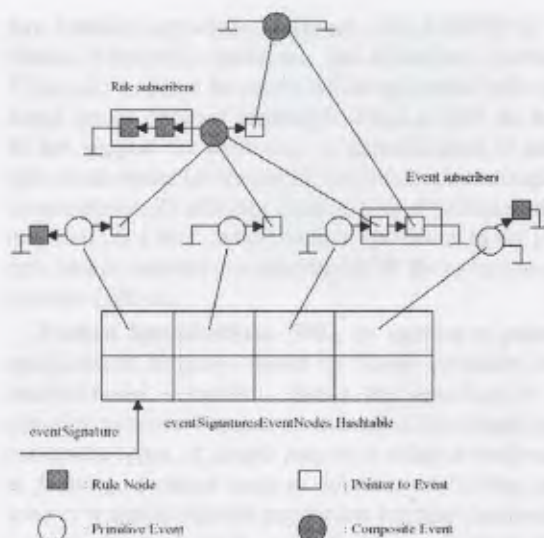
of events detected without affecting the application semantics. These were identified after considering classes of applications with certain common properties. For example, sensor applications generate events (e.g., temperature, pressure values) where each occurrence refines the previous value and hence the latest value is of interest when multiple occurrences are present. This observation can be effectively used to prune the events that will not be needed and retain only those that are relevant. This has an impact both on the space requirements as well as the complexity of algorithms used for event detection. The following event consumption modes were defined and supported in the local event detector (or LED) that implemented the detection of Snoop expressions.

- Recent: only the most recent occurrence of the initiator for any event (primitive or composite) that has started the detection of that event is used (useful for sensor class of applications)
- Chronicle: the initiator-terminator pair is unique for an event occurrence (applications where there is a need to match events, such as bug_report and bug_fix)
- Continuous: each initiator of an event starts the detection of that event (for applications requiring moving window concept, such as stock monitoring)
- Cumulative: all occurrences of an event type are accumulated as instances of that event until the event is detected (applications such as a bank where accumulated events are applied at the end of the day)

The operators supported in Snoop are: disjunction (OR), conjunction (AND), Sequence, Periodic (with a cumulative variant), Aperiodic (with a cumulative variant), non-occurrence (NOT), and temporal (both absolute and relative). The primitive events were domain specific (finite and pre-defined for a domain) and the event expressions were domain independent. For example, relational domain consisted of insert, delete, and update events whereas in an object-oriented domain invocation of any method of any class acted as an event. To add expressive power, begin and end events were defined so that start and end of a function (or any interval) could be broken up into separate events.

Rules in the form of condition and action were associated with primitive as well as composite events. Multiple rules could be associated with an event and a priority could be specified. Concurrent and cascaded execution of rules were supported. Execution models were developed to support rule execution semantics [1, 55, 56]

With point-based semantics, LED [5] uses an event detection graph (or EDG) as shown in Figure 1 for representing an event expression specified using Snoop. This representation is in contrast to other approaches such as Petri nets used by Samos [22, 23] or an extended finite state automata used by Compose [15]. By combining



event trees on common sub expressions, an event graph is obtained. Data flow architecture is used for the propagation of primitive events to detect composite events. All leaf nodes in an event tree are primitive events and internal nodes represent composite events. By merging common subgraphs, the same event is not detected multiple times. In addition to reducing the number of detections, this approach saves a substantial amount of storage space (for storing partial event occurrences and their parameters), thus leading to an efficient approach for detecting events. Event occurrences flow in a bottom-up fashion. When a primitive event occurs and is detected, it is sent to its leaf node, which forwards it to one or more parent nodes (as needed) for detecting one or more composite events. When composite events are detected, associated rules are triggered. This representation is similar to the query graph used for query evaluation in a DBMS and allows set-based computation (or multiple events detected at a node). Optimizations can be performed by rewriting event expressions and generating the event graph after the optimizations are performed.

Point-based semantics worked well for most applications. However, when certain operators were composed in a particular way, Galton [57] pointed out that the point-based semantics failed and detected composite events which were non-intuitive. This, for example, happens when the sequence operator is composed twice. This brought out the limitation of the point-based semantics and the need for a more complex semantics that used intervals instead of a point for composite events. As a re-

sult, SnooP [58, 59, 60, 54] was developed for all the operators and event consumption modes (except chronicle) of SnooP.

Briefly, interval-based semantics associated two time points with each event: start time and end time. For primitive events, both are same. For composite events, the start time of the initiator and the end time of the terminator are used as the interval in which the composite event occurs. Allen's [61, 62] temporal combinations are used to determine the relevance of the intervals for a particular operator. Neither the event graph nor the detection approach changes with the introduction of the interval-based semantics. Only the algorithms used at each node is different and in fact both point- and interval-based semantics can be supported in the same system.

3. Novel Applications of the ECA Paradigm

As discussed in Section 1, the ECA paradigm has been used in databases as well as stand-alone applications. A number of products support the paradigm in various ways at different levels of abstraction in distributed information exchange, topic-based event notification, as part of information bus, etc. As we will briefly discuss later (Section 4), events and rules are being incorporated into XML and other standards for wider usage and applicability.

In this section, we will discuss four novel applications where we have effectively used the ECA paradigm with minor modifications and adaptation. In fact, we have been able to reuse the entire LED code base (in Java) for these applications.

Information filtering [63, 64, 65, 66, 67] is the process of extracting relevant or useful portions of documents from continuous streams of textual data based on relatively static user-provided patterns. On the other hand, *Information Retrieval* [68, 69, 70, 71] is the process of extracting relevant or useful portions of documents from a relatively static collection of documents based on a stream of incoming user patterns (or queries). Extant information filtering systems and search engines support only keyword searches and Boolean operator queries. Monitoring text streams for complex patterns have far reaching implications, such as tracking information flow among communications, web parental control, and business intelligence.

Consider a real world example where an analyst is tracking information streaming from various resources. He/she is interested in the occurrence of the word "bomb followed by the word "ground zero occurring twice, along with the word "automotive or its synonyms (i.e., ("bomb FOLLOWED BY "ground zero) occurring twice) AND "automotive (or its synonyms)). This pat-

tern contains keywords, sequence (FOLLOWED BY), phrase, frequency, synonyms, and a Boolean operator. This pattern cannot be expressed using current informational query retrieval languages (IRQLs) [69] as they do not support the following: i) quantification of multiple occurrences (or frequency) of patterns and complex compositions, ii) arbitrary composition of pattern operators, and iii) a user cannot include synonyms in the pattern, and is required to explicitly list all the synonyms as separate patterns.

Pattern Specification: PSL, an expressive pattern specification language based on Snoop operators and interval-based semantics, allows the specification of complex patterns. Patterns are classified into simple and composite types. A *simple pattern* is either a word such as *filtering*, a phrase such as *information filtering systems* or a simple regular expression (regular expression on a single word) such as *info**. The occurrence of a simple pattern is denoted by $P[Os, Oe]$, where $Os = Oe$ (i.e., the starting and ending offset of a simple pattern is the same). PSL supports two types of simple patterns, system-defined (e.g., *BeginDoc* and *BeginPara*) and user-defined (single word, phrase and regular expression). A *composite pattern* is an expression constructed using simple patterns, previously constructed composite patterns, PSL operators and options. PSL provides a comprehensive set of operators, OR, non-occurrence (NOT/N), sequential (FOLLOWED BY/N), structural (WITHIN/N), frequency (FREQUENCY/N), proximity (NEAR/N) and the option SYN that allow users to compose *complex patterns*. Table 1 shows various operators and their functionalities with examples. For detailed explanation of PSL, please refer [72]. The semantics of the operators are exactly the same as that of Snoop except that the offset from the beginning of the document is used instead of time. In addition, *N* specifies the maximum distance between the begin offset and end offset. From the table, it is straightforward to infer the similarity between Snoop operators and PSL operators. Frequency is a new operator introduced for information filtering. When we analyzed the requirements of this domain with respect to the multiple occurrence of the same pattern, it was clear that the recent context was not appropriate. In information filtering, you want to not only use the last closest occurrence, it does not make sense to reuse the same pattern for another composite pattern detection. As a result, the recent context was modified to the *proximal-unique*. A new context was added to the algorithms of the interval-based semantics. For details refer to [72].

Pattern Detection: A user *pattern* is represented as a pattern detection graph (same as the event detection graph). Simple patterns form leaf nodes. Composite patterns form intermediate nodes. Grouping of subpatterns

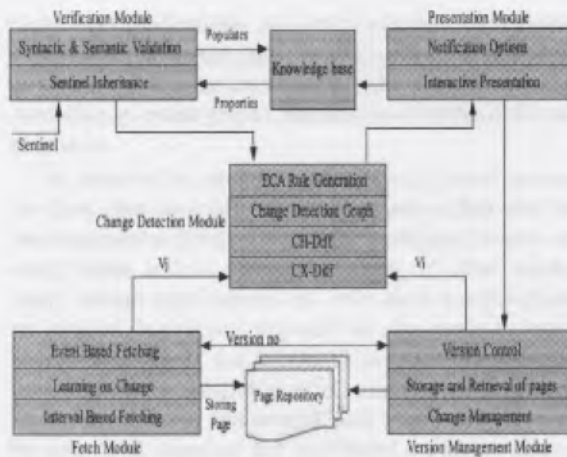
Operator	Purpose	Examples
OR	Provide optional criteria in specifying patterns	"bomb" OR "explosive" "/bomb" NEAR2 "automotive" OR "/bomb" NEAR "building"
NOT	Exclude patterns that are not to be detected Exclude patterns with number of pattern occurrences exceed a user specified number Exclude patterns within predefined simple patterns	NOT ("retiree") ("information", "filtering") NOT2 ("retiree") ("information", "query language") NOT ("information" FOLLOWED BY "retiree") (BeginPara, "EndPara")
NEAR	Detect patterns that occur within a words of each other Detect patterns that occur within the same document	"information" NEAR2 "filtering" "information" NEAR2 "filtering"
FOLLOWED BY	Detect patterns that occur in certain order within a words of each other Detect patterns that occur together in certain order within the same document	"date" FOLLOWED BY2 "structures" "date structures" FOLLOWED BY "algorithm"
WITHIN	Define the scope of detection within a document, a paragraph or a sentence Define a range for detecting patterns within a document	("information" NEAR "retiree") WITHIN (BeginPara, EndPara) ("information" NEAR2 "retiree") WITHIN ("InfoFilter", "Paraphrase")
FREQUENCY	Define minimum number of occurrences of a pattern	Frequency/5 "freq"
SYN	Keyword synonyms	"bomb" SYN

is also done for efficiency. Data flow is used to notify the occurrence of simple patterns to leaf nodes, which in turn propagate them to intermediate nodes. To handle synonyms, WordNet [73] is used to determine the synonyms of the patterns, if the synonym option is specified. The incoming stream is processed to generate simple patterns to be fed to the pattern detection graph. Words are also sent to WordNet for extracting their synonyms. Once the synonyms are extracted, they are stored and compared with incoming words using a suffix trie. Given a stream, tokens (corresponding to patterns) are generated along with their offset and are notified to the leaf nodes. Detection of composite patterns is the same as the detection of a composite event.

The above system designed earlier for streams has been extended to handle stored data as well [71]. The stored data (e.g., web directory) is indexed where the index keeps the offset information of each word along with the word. With this, it is possible to search for patterns using a stored index instead of streaming. Most of the system is common to these two except for a couple of modules. For details, refer to [71].

A number of situations require monitoring changes that are made to one or more documents in a large distributed repository (e.g., select web pages). This is especially useful in the context of web where, currently, a significant amount of time and resources are spent by individuals for monitoring changes to web pages manually. By automating this approach, relevant, useful, and timely notifications can be sent to users.

WebVigil is a profile based change detection and notification system that monitors changes to structured and



unstructured documents. Currently it handles HTML and XML documents. WebVigil architecture is modular and extensible. It has been designed to handle expressive change specification, provide truly asynchronous approach to manage user's requests, detect actual changes, and notify changes – all using active capability. Figure 2 illustrates the architecture of WebVigil.

WebVigil accepts profiles (or sentinels) from users and monitors for user-specified changes in an intelligent manner (using a combination of intelligent pull and push) and notifies the user in a timely manner of the changes. The profile (given by the user) can include monitoring over a period of time, specifies one or more url's to be monitored, and the types of changes to be monitored (any change, keyword, phrase, link, image), and how the changes should be notified. Even composite changes such as conjunction, disjunction, and non-occurrence can be specified. The versions of the pages on which change needs to be computed (pair-wise, every n , moving n) can also be specified.

Of all the modules shown in Figure 2, the change detection module is central to the system and heavily uses the active capability (actually LED and modified LED for change detection) in a novel way. Change detection module contains ECA rule generation, Change Detection graph, CH-Diff [74, 75] and CX-Diff [76, 77, 78] as its sub-modules. ECA rule generation module is responsible for activation and deactivation of profiles, generating fetch rules for retrieving pages, detecting events of interest and to generate time-based notification of changes. Change Detection Graphs reduce the amount of information stored, if more than one user requests for different types of changes on the same page. CH-Diff supports change detection in HTML pages whereas CX-Diff is for XML pages. The change detection is done by ex-

tracting appropriate objects from the pages based on the change type specified by the user. The objects are then compared for changes and if there are any, they are reported to the notification module.

In order to monitor the page specified by the user, it has to be fetched using the specified periodicity. In WebVigil, we use the *periodic* event to achieve this fetch in an asynchronous manner. A periodic event is an event that repeats itself within a constant and finite amount of time. The initiator and terminator are the start and end events of a sentinel and t is the interval with which the page should be monitored. The actual fetch of the page is performed by the rule associated with the periodic event. Profiles in WebVigil can be classified into two categories: Fixed fetch-Interval and On-Change. The rules associated with all the events (absolute, relative, plus and periodic) generated are executed in the immediate coupling mode. In this manner, ECA rules are used to asynchronously activate (enable) and deactivate (disable) profiles at run time. Once the appropriate events and rules are created, the local event detector handles the execution at run time. Fetching of a page is considered an event that starts the process of change detection. Each type of detected change is considered an event that is propagated to detect composite events. The WebVigil system detects these events for each document (page) on which a profile is set. The system also detects composite events. A composite event is an event expression comprising a set of events related through one or more event operators such as NOT, AND, OR.

WebVigil has adapted and extended the event detection graph approach used in Snoop for detecting primitive as well as composite changes. Primitive change detection involves detecting changes to links, images, phrases, keywords, etc., in a page. The system has been implemented and is available for use at <http://itlab.uta.edu/berlin:8080>

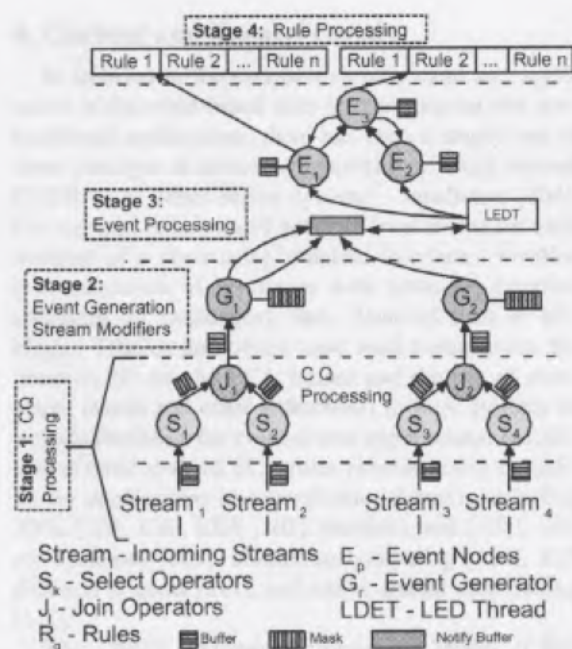
Event processing and lately stream data processing [79, 80, 81, 82, 83, 84] have evolved independently based on situation monitoring application needs. As we have discussed, several event specification languages for specifying composite events have been proposed and triggers have been successfully incorporated into relational databases and applications. Recently, stream data processing has received a lot of attention, and a number of issues – from architecture [79, 81, 82, 83, 85] to scheduling [86, 87, 88, 89] to Quality-Of-Service (QoS) management [90, 91, 92] – have been explored. Although both of the above topics seem to be different on the face of it, we believe, based on the applications we have analyzed, that they augment/complement each other very well in terms of computational needs of

real-world applications. As it turns out, the computation model used for stream data processing (data flow model) is not very dissimilar from some of the event processing models (e.g., event graph), but developed with a different emphasis.

As many of the stream applications are based on sensor data, they invariably give rise to events that need to be composed to detect composite (or complex) events on which some actions need to be taken. In other words, many stream applications not only need computations on streams, but these computations also generate interesting events (e.g., car accident detection and notification, network congestion control, smart homes, network fault management) and several such events may have to be composed, detected and monitored for taking appropriate actions. Currently, to the best of our knowledge, none of the work addresses the specification and computation of the above two threads of work and the issues that need to be addressed. A number of sensor database projects, Cougar [93, 94], TinyDB [95, 96] have tried to integrate the event processing with query processing under a sensor database environment. However, the event-driven queries proposed in TinyDB, for example, is used to activate queries based on events from underlying operating systems. Our focus in this work is to process large number of high volume and highly dynamic event streams generated from continuous queries for the applications that need complex event processing and CPU-intensive computation (i.e., CQs) for generating events. Our premise is that although each one is useful in its own right, their *combined* expressiveness and synergistic integration are critical for a large class of current and future applications of stream data processing.

Our integrated model [97, 98, 99] shown in Figure 3 consists of four stages: 1) CQ processing stage used for computing CQs over data streams, 2) event generation stage that is responsible for generating events that are only of interest to the event processing stage (using the notion of masks and other constraints), 3) event processing stage that is used for detecting composite events, and 4) rule processing stage that is used to check conditions, and to trigger predefined actions once events are detected.

The above architecture is possible as both of our stream and event processing models use the *same* data flow architecture and the operators form an event graph or a query graph. Use of other event detection approaches, such as Petri nets and extended automata would have made the architecture more complex and afford less scope for seamless integration. The interface between the two has been designed to avoid interprocess communication and seamless specification of continuous queries and event expressions that can be combined in arbitrary ways.



The LED has been used almost unchanged for the above integration. The event generation stage was added to combine the two relatively easily. Of course, a number of additional issues still need to be addressed in the above integration which can be found in [97, 98].

Controlling access decisions for resources is critical in any system or environment. Dynamically monitoring the state changes of an underlying system or environment, detecting and reacting to changes without delay are crucial for the success of any active security and access control enforcement mechanism. With their inherent nature, ECA rules are prospective candidates to carry out change detection and to provide both access control and active security. Role-Based Access Control (RBAC) has been considered as a viable alternative to both discretionary and mandatory access control and is shown as cost effective and is being employed in various domains on account of its characteristics: rich specification, policy neutrality, separation of duty relations, principle of least privilege, and ease of management.

Enterprises can model access control policies using either the RBAC standard [100] or any of its extensions. Both the *specification* and *enforcement* are critical in employing these policies in real-world systems. Most of the research has *explored* and *extended* RBAC. On the other hand, most of the current systems have concentrated mostly on policy specifications and very little on

the ease of their enforcement. ECA or Active rules not only have a well-defined semantics, they can be added to existing systems and executed to *enforce access control policies* if the policies can be mapped to active rules. We have shown how active authorization rules or extended ECA rules can be used to enforce RBAC and its extensions such as temporal, and control flow dependency constraints in a uniform way [101].

Constraints such as time-based, context-aware and others play a vital role in providing fine grained access control and realizing RBAC over diverse domains. We have extended the standard RBAC with constraints based on event patterns (generalized event expressions) that are not supported by current systems. Event patterns with complex events and simple events as constituent events were used to model constraints such as temporal, context, precedence, dependency, non-occurrence, and their combinations. We have extended event detection graphs as event registrar graphs to incorporate all the event generalizations and for capturing event occurrences and keeping track of event ordering. We have shown how enhanced ECA rules and LED are used for enforcing RBAC standard together with the proposed extensions in a uniform and transparent manner.

In this application, we have extended and generalized the ECA paradigm. Attribute-based semantics, masks, and other constraints were needed to specify complex access control policies. The extension of the ECA paradigm has also resulted in some extensions to the event detection graph. The main advantage of our approach (over other extant approaches) is that ours provides a *uniform framework* for specifying RBAC policies as well as enforcing them directly in the underlying system. A number of advantages including separation of policy from system code, ability to change rule sets dynamically, accrue from our approach.

Above, we have described the adaptation of the ECA paradigm for several newer applications. The diversity of applications indeed indicate the ubiquitous nature of this paradigm and how it can be adapted meaningfully for event-driven as well as other applications. As a matter of fact, in addition to the above applications, we have also shown how the ECA paradigm can be used as a mechanism for executing work flow instances by activating and synchronizing task executions using Snoop operators and ECA rules [102]. We have also shown the sufficiency of Snoop operators for supporting work flow specification recommended by WMC (Workflow Management Coalition) [103].

4. Current and Future Trends

In addition to the extensive development and application of the event-based rules in conventional and non-traditional applications, there has been a steady use of these concepts in several commercial products beyond CORBA and other earlier systems. JavaBeans [104], for example, incorporated attribute level events for each attribute of a class using standard interface. InfoBus is an extension of JavaBeans with advanced dynamic interfaces for exchanging data. Vendors such as Weblogic, TIBCO, and others have used event-driven approaches (if not the ECA format and the use of composite events and other extensions) in their systems to provide flexibility for event-driven applications. In addition to these systems ECA rules provide active capability for *applications* in several other *domains* including XML [105, 106], RDF [107], semantic web [108], sensor databases [109], ubiquitous computing [110], P2P database systems [111], and active spatial data mining [112].

The DMTF Common Information Model (CIM) [113] is a conceptual information model for describing computing and business entities in enterprise and Internet environments. It provides a consistent definition and structure of data, using object-oriented techniques. The CIM Schema establishes a common conceptual framework that describes the managed environment. The CIM Event Model defines the Event-related abstractions. It describes the CIM Indication hierarchy and the use of Indications to model Events. The Event Model also describes the use of subscriptions to register to receive Indications. This is another area where we will see the utilization of the ECA paradigm coming to fruition.

Autonomic computing has become extremely important. To manage interdependent usage of various resources (may they be DBMSs, web gateways, communication pipes), there is a need for managing various policies that govern individual resources, but have an impact on policies of other resources. So it is extremely important to manage policies in a distributed environment. Several groups including IBM and other players are working on the flexible management of policies in an autonomic computing environment. Here again the advantages of the ECA paradigm and rules are quite evident. Work along the lines of policy analysis, identifying conflicts, dynamic change of policies, and triggering policy changes based on distributed state of the system will become extremely important.

As XML is a widely used standard for information exchange (self-describing format), there have been attempts at incorporating ECA paradigm [105] and other event-related features into XML. In addition, a number of companies are working together for defining web services policies (WS policies) [114] now using XML,

SOAP, and WSDL extensible models. There is ongoing work on defining declarative policy specification languages for web using Rule Markup language (or RuleML) [115].

Both stream processing (e.g., Streambase [116], Apama [117] MavEstream [99]) and pervasive computing are poised to take off on account of the availability of smart sensors (e.g., RFID's) for use in large quantities. This will increase the amount of data that will be generated which will have to be aggregated and abstracted in novel ways. Both stream processing and concomitant event processing will play critical role in the successful deployment of these technologies.

5. Conclusions

The purpose of this paper was to trace the history of event-based computation over the past 2+ decades and how it has been used in many diverse applications. Due to space constraints, we did not discuss earlier work on exceptions in programming languages and operating systems and some of the work in AI that formed as precursors to the development of this paradigm. It is amazing that the work which started out with the intention of automating a number of applications in simple ways has lasted this long and it only seems to be gaining momentum. All the applications and associated systems described in this paper have been implemented as proof-of-principle systems.

Beyond the applications briefly outlined from the viewpoint of the usage of the ECA paradigm, currently, we are working on various capabilities that utilize ECA rules: extending and adapting the ECA rules for use in information assurance, attribute-based semantics for event operators for utilizing in advance applications, synergistic integration of distributed events and their detection (or the global event detector or GED) with stream processing system, and embedding ECA capability into XML for supporting business policies, negotiations and access control/security aspects of e-commerce.

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Abstract

This paper retrospectively analyzes the progress of event-based capability and their applications in various domains. Although research on event-based approaches started in a feasible manner with the intention of incorporating triggers in database management systems for monitoring application state and to enhance application by reducing/minimizing user intervention, eventually it has become a force to reckon with in a wide variety of diverse domains. This is primarily due to the fact that a large number of real-world applications are event-driven and hence the paradigm is applicable.

In this paper, we briefly overview the development of the ECA (or event-condition-action) paradigm. We briefly discuss the evolution of the ECA paradigm (or active capability) in relational and Object-oriented systems. We then describe several diverse applications where the ECA paradigm has been used effectively. The applications range from customized monitoring of web pages to specification and enforcement of access control policies using RBAC role-based access control. The multitude of applications clearly demonstrates the ubiquitous nature of event-based approaches to problems that were not envisioned as the ones where the active capability would be applicable. Finally, we indicate some future trends that can benefit from the ECA paradigm.

1. Introduction

In the mid and late eighties, the inability of database management systems (DBMSs) to monitor and trigger

events and notifications even for conventional applications such as inventory control (e.g., a part needs to be reordered when quantity on hand decreases below a specific number) prompted the work on automating the above to reduce or eliminate user intervention. At that time, process control applications had the capability to monitor system state and take appropriate actions. However, most of these systems were custom-developed and spanned for real-time operations and did not use a general framework for the purpose of monitoring and automation. A number of efforts at that time examined a large number of applications from diverse domains such as process control, power distribution, stock trading and portfolio management, network management, and the use of database in monitoring applications with the goal of developing a framework that could be used for all monitoring applications. Timeliness, near real-time response, well-defined semantics, and the ease of management of the system were the goals of this research and development.

The early explorers of the relational concepts for monitoring were: HPAC [1], Porgues [2], and ETM [3]. Although all of them had the same broader goal, their approaches and how they addressed the problem were very different. HPAC, perhaps, took the most general approach of incorporating monitoring into a DBMS by extending the impact on all components of a DBMS: knowledge model (or specification), query optimization, transaction management and recovery. The separation of an event from condition and action was proposed based on the role of their semantics as compared to other relational approaches of that time. The event component was separated for the first time and event operators (aggregation, sequence, and closure) were proposed. Coupling modes

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